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REVIEW

An overview of Cladoceran studies conducted in mine water impacted lakes

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Abstract Mine-fed waters have been rigorously studied, but most of the ecological research on mine water has been conducted in riverine systems. Lakes, however, are known to recover from pollution more slowly than riverine systems and, thus, the impacts of mine water on lakes are equally interesting. One of the most important biological components in lakes are the Cladocera, an order of crustacean zooplankton. Cladocerans are regarded as excellent indicators of environmental change and, for example, genus Daphnia is one of the most used test organisms in ecotoxicology. While in vitro tests regarding pollutants and cladocerans have been reviewed multiple times, the literature regarding the community level responses to mine pollution in natural settings is still to be better explored. The main aim of this paper is to screen and compile the current literature related to cladoceran communities and mine-induced water pollution. In addition, the applicability of cladocerans as a bioindicators group in mine water studies will be explored. This review shows that cladocerans have been studied in many cases of mining related pollution and most of the research has been conducted in North America, central Europe and Brazil. Acidity, turbidity and metals pollution are nearly equally important in shaping cladoceran communities in mining impacted lakes. The most tolerant taxa to mining pollution are *Bosmina* spp. and *Chydorus sphaericus*. The group clearly has potential as community level bioindicator/biomonitor in mining pollution studies, but challenges remain. Namely, the lack of data regarding the most sensitive taxa is a major problem when indicator value of any single species is assessed.

Keywords Mining · Pollution · AMD · Tailings · Zooplankton · Water flea

Introduction

Although the reservoirs of high grade deposits are continuously decreasing (Watling 2015), the total mineral production has actually doubled in the past 30 years (Reichl et al. 2016). The increased exploitation of low grade ores results in higher amount of mine waste (Hudson-Edwards and Dold 2015) and, in many cases, subsequently larger quantities of potentially harmful mine water. Thus, there is a growing need for monitoring tools, which are suitable for reliable assessment of ecological conditions in mine water impacted lakes. Potentially harmful mine waters are known to exhibit a wide range of acid to alkaline conditions (pH − 2.5 to 11.7) and based on chemical composition, mine water can be characterized in a plethora of ways (e.g., saline, radioactive, corrosive or toxic; Nordstrom 2011). However, the environmental impacts of mine water are even

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more diverse. This is mainly due, but not limited to, the variability in species sensitivity to harmful substances and to the physical and chemical characteristics of the receiving environment (e.g., Kozlova et al. 2008). Environmental impacts of mine waters on lakes have been acknowledged for centuries (e.g., Walder and Nilssen 2005) but because the effluent is usually released into lotic (flowing) waters, this has gained most of the attention in research. While riverine systems are known to recover fast when pollution stops (Yount and Niemi 1990), lakes tend to recover slowly because of longer residence times. In some cases, the recovery may be further delayed by sedimentary contamination (Rogalski 2015) and mine water induced meromixis, especially in pit lakes (e.g., Schultze et al. 2017).

Bioindicators/biomonitors are attractive tools for pollution researchers. The idea is that the biota is the best indicator of ecological changes as it provides the data concerning the actual biological impacts (Zhou et al. 2008). In mine water studies, the popular bioindicator species are riverine insect larvae (Cain et al. 1992; Salmelin et al. 2017) and acidophilic algae (e.g., Valente and Gomes 2007). In lakes, one of the most promising indicator groups for mine pollution is the Cladocera; an order of microscopic aquatic Crustacea, which are excellent indicators of environmental change (Jeppesen et al. 2011). Cladocera colonize almost every type of fresh waters and they are usually highly abundant. The group is of vital importance to the wellbeing of aquatic systems due to their position in food webs. Cladocerans transfer energy from primary producers towards higher trophic levels, such as juvenile fish (Sterner 2009).

There is a large body of knowledge regarding the effects of harmful substances on cladocerans from in vitro testing (Sarma and Nandini 2006; Suhett et al. 2015). In fact, the applicability of cladocerans to mining contamination assessment is further highlighted in Canadian metal mining effluent regulations (Canadian Government 2002), which include *Daphnia magna* monitoring tests to be conducted on a monthly basis as a part of mine water monitoring programs. Despite the obvious advantages of in vitro studies (standardized protocols, low cost), the comparability of in vitro tests with changes in situ is not well understood. Whereas the results of ecotoxicological laboratory tests using Cladocera have been reviewed several times (e.g., Sarma and Nandini 2006; Persoone et al. 2009; Bownik 2017), the impact of mine water on natural cladoceran communities has not been reviewed.

This contribution focuses on the effects of mine-impacted waters on lentic cladoceran communities and populations in an attempt to compile relevant studies. The second goal is to assess the suitability of cladocerans as a community-level bioindicator tool in studies of mine-related lake pollution.

Scientific bibliographic databases (BioOne, EBSCO, Web of Science, Google Scholar) were used to find the research literature considering the impacts of mine water release or tailings dumping on cladoceran communities (search terms cladocera AND mining, cladocera AND AMD, cladocera and mine water, cladocera AND tailings, cladocera AND acid mine drainage). Because the mine water impact is difficult to differentiate from other stressor sources in the catchment and airborne pollution, only the cases where point sources are clearly identified are reviewed here. In addition, all in vitro tests are omitted from this review whereas mining pit lakes and man-made reservoirs are included and are discussed together with natural waterbodies.

Mine water pollution as a multi-stressor problem

The mine waters only rarely contain a singular component, which can be deemed as a single factor which induces ecological impacts. Mine waters can simultaneously exhibit high metals concentrations, elevated salinity and high concentrations of solids and these different constituents and characteristics affect each other. For example, pH and redox potential can be regarded as the most important parameters which control the solubility, and thus the availability, of trace metals to biota. The processes involved are precipitation, adsorption, oxido-reduction and complexation (Bourg and Loch 1995). Toxicity tests for Cladocera are being designed to discriminate the toxicity due to metals and low pH (Lopes et al. 1999) and the bioavailability of some metals can be assessed using biotic ligand models (BLM), where local water characteristics are taken into account (Niyogi and Wood 2004). However, all BLM tools have pronounced applicability ranges for many parameters (e.g., pH, DOC, Ca, Mg, Na, SO; Vink and Verschoor 2010). Further, in some cases, mine effluent affects these parameters and subsequently hampers the analysis of the mine water impact. Thus, the issue is complicated by the synergic or antagonistic effects of mine water components (e.g., metals; Smirnov 2017). In addition, the varying effects of contaminants also depend on the route of exposure (e.g., dietary exposure, direct exposure; Sofyan et al. 2009). Even though the environmental impacts of elevated salinity and dissolved solids have not been studied as intensively as acid drainage in mine water research, they constitute an important and potentially critical component in mine water toxicity. Salinity (sulfate, sodium, calcium) induces osmotic stress to fresh water biota and may turn the water body meromictic (Molenda 2014). The meromixis is a result of the incomplete mixing of dense (saline) effluent and overlying freshwater which may lead to permanent anoxia in deep bottoms. The elevated concentrations of solids may contribute to habitat degradation due to diminished water clarity and elevated siltation. Further, elevated concentrations of suspended minerals (turbidity) are harmful to cladocerans (McCabe and O'Brien 1983; Cuker 1987; Hart 1987; Kirk and Gilbert 1990). In addition, the accompanying impacts (changes in water clarity, trophic status, acidification, predator community or food availability) may induce additional difficulties in mine pollution research. Due to the complex character of mine pollution, the most convenient way to present the current research is to organize the literature based on mined material rather than pollutant.

Cladocera and metal mining

Bauxite

Lake Batata, located in Amazonia, Brazil has been impacted by bauxite mining tailings, which are high in very fine solid particles and in aluminum and iron oxides. The tailings were dumped into the lake for 10 years (18 million m^3/year), which has resulted in greater variation in cladoceran density and brood size when compared to a non-impacted area (Bozelli 1996). In addition, cladocerans collected from impacted site showed smaller body sizes but higher weights which were explained by ingestion of tailings material (Maia-Barbosa and Bozelli 2005). Moreover, a 7-year study indicated that the highest impact of tailings was detected during the low water period and that *Diaphanosoma birgei* and *Bosmina hagmanni* dominated during the turbid phases (Garrido et al. 2003) suggesting high tolerance to turbidity, whereas *Moina minuta* was negatively impacted by high turbidity. Thus, *M. minuta* would be interesting species if the impacts of suspended solids pollution were to be assessed in the future studies in the region. The impact of seasonal water level fluctuations, which also result in changes in turbidity, is characteristic in these studies. Therefore, it is difficult to postulate the most important stressor, because other season-related environmental conditions (e.g., temperature, food availability) probably vary simultaneously with the turbidity. The ingestion of tailings particles by cladocerans is potentially highly important component when ecological impacts of tailings are considered because species exhibit morphological differences of feeding apparatus, which has been suggested to contribute to the ability of selective (e.g., ability to reject inedible particles) feeding (Smirnov 2017).

Copper and gold

Doig et al. (2015) investigated the impact of acid and metal-contaminated effluent originating from Cu–Zn mine on *Bosmina longirostris* abundance in a small boreal lake in Manitoba, Canada. The authors detected severe reduction in community size, which was related both to acidity and zinc contamination. Similarly, Kerfoot et al. (1999) detected a pronounced decline in *Bosmina* production in oligo-mesotrophic (pH 6.5–9.1) lake, Keweenaw Waterway in Michigan USA, due to copper pollution (maximum copper sediment flux 579 μg/cm^2/yr) inflicted by historical (1848–1920) mining activities. Different cladoceran species exhibit high variation in copper tolerance (12-fold differences in copper tolerance have been reported; Bossuyt and Janssen 2005). *B. longirostris* is regarded as more sensitive to copper pollution than many other cladoceran species (Koivisto et al. 1992; Koivisto and Ketola 1995; Bossuyt and Janssen 2005) which may explain the above mentioned deleterious impact. Leppänen et al. (2017b) reported decreased diversity and species richness in Lake Kirkkojärvi, southern Finland, which has been affected by increased input of mineral matter and minor metal pollution, originating from tailings impoundment of Au–Cu mine around 1960–1970, but the lake has never acidified due to rapid dilution. The most pronounced impact was detected during the input of fine mineral tailings. *Polyphemus pediculus*, *Eubosmina coregoni*, *Daphnia* sp., *Alonella excisa*, *A. quandranqularis*, *Alonopsis elongata* and *Disparalona rostrata* were negatively affected. In addition, the cladoceran community in the shallow embayment of the same lake is unharmed by low volume but continuous high-Cu low pH effluent (since 1970s) because the pollution is most intense during early spring, when the cladoceran communities are mostly absent (Leppänen et al. 2017a). The lucky mismatch is further reflected in increased abundance of *B. longirostris*, which is especially sensitive to copper pollution but thrives in eutrophicated systems, such as Lake Kirkkojärvi.

Iron

Holopainen et al. (2008) reported potassium to be the most harmful element to the planktonic ecosystem in Russian lakes impacted by alkaline mine water released from iron mine. Species number was low (< 7) and the impacted lakes (pH 7.7–8.0, EC 49–391 µS/cm) were dominated by *B. longirostris* whereas in the non-impacted reference lake (pH 6.7–6.8, EC 24–28 µS/cm) the dominating species was *Daphnia cristata*. The elevated conductivity of the impacted lake may explain the dominance of *B. longirostris,* a species known to inhabit high conductivity waters (Zawisza et al. 2016). In contrast, Bradbury and Megarad (1972) found that the cladoceran community in Shagawa Lake (Minnesota, US) shifted from a *B. longirostris* dominated system towards higher abundance of *Chydorus sphaericus* due to onset of anthropogenic eutrophication and the effluent (hematite rich effluent) originating from iron mine. The authors suggest that the reason for species shift is related to cyanobacterial blooms, but still, this trend is very interesting, because both species are regarded to prefer eutrophicated waters (e.g., Nevalainen and Luoto 2013) and to tolerate cyanobacterial blooms (Tõnno et al. 2016). However, the species differ in their tolerance on heavy metals (Bossuyt and Janssen 2005) and solids pollution (elevated conductivity; Zawisza et al. 2016). However, no metals concentrations data are available from Lake Shagawa. Changes in species assemblages are also reflected in species richness as Winegardner et al. (2017) reported the pronounced decrease in cladoceran species richness to correlate with iron mining derived metal pollution in Quebec, Canada. In species level, *C. sphaericus* was able to remain relatively unharmed by pollution. Moreira et al. (2016) compared zooplankton communities in two artificial lakes, in Mata Porcos, Brazil, which receive mining effluent from two different mines. The cladoceran community in the lake which was affected by kaolinite mining (pH 6.8–0.7.1, EC 12.1–16.2 µS/cm, barium 24.0–53.3 µg/L, manganese 66.3–248.7 µg/L, zinc 0.0–12.5 µg/L) was dominated by *B. longirostris*, whereas the cladoceran assemblage was more diverse (*Eubosmina tubicen, Bosminopsis deitersis, Alonella clathratula, Ilyocryptus spinifer*) in the lake which was affected by iron mine effluent (pH 5.4–6.4, EC 2.9–18.1 µS/cm, barium 4.2–6.9 µg/L, manganese 12.4–109.7 µg/L, zinc 4.2–68.9 µg/L). Here, despite some differences in water chemistry between two lakes, the reported concentrations are low in terms of toxicity (ECOTOX 2017) and no clear reason behind the community differences can be drawn from the water chemistry alone.

Nickel, tin and zinc

Saline and metal-contaminated mine water originating from Talvivaara Terrafame Ni-Zn-Cu mine (central Finland) resulted in nearly total disappearance of *Daphnia cucullata* and clear dominance of *B. longirostris* and turned the receiving lakes meromictic with maximum concentration of 1200 mg/L of sulfate in surface water. Whereas the metals concentration in lake water has remained relatively low, the salinity-induced stress and the stratification of the waterbody (and resulting physical changes in lake) probably contributed more to the community change (Leppänen et al. 2017c). The cladoceran production greatly diminished and clear changes in species composition were detected in Datun Lake, China, which was impacted by mineral tailings and elevated arsenic concentrations originating from tin mining. Particularly, *Eubosmina longispina* and *Alona guttata/rectangula* were adversely affected as the production declined over 80% (Chen et al. 2016). Wilk-Woźniak et al. (2011) studied plankton communities in fishponds contaminated by heavy metal runoff from Zn-Pb mine “Matylda” in south Poland and found an extremely poor cladoceran community. The maximum proportion of cladocerans among zooplankton was only 3% (total density) and the only reported species was *E.coregoni*.

Uranium

Ferrari et al. (2009) reported *Bosmina sp*. as the only species in waste water of a uranium mine in Poços de Caldas Plateau region, Brazil, with elevated conductivity (2415 µS/cm) pH of 3.9 and high uranium concentration (4.3 mg/L). However, also the low impact reference lake was noted as being unsuitable for cladocerans as only 2 species (*Diaphanosoma* and *Bosmina*) were recorded. The reference lake is characterized by fluctuation in the water properties (e.g., SO_4^{2-} 12.4–253.4 mg/L, hardness 41.49–323.4 mg/L) (Ferrari et al. 2017) which may explain the low cladoceran diversity. In addition, *Bosmina* –group species (*Bosminopsis deitersi* and *Bosmina* sp.) were detected to be the only cladoceran taxa in a newly formed acidic uranium pit lake in the same region with mean pH 3.8, electrical conductivity of 2391 µS/cm, sulfate concentration of 1413 mg/L and uranium concentration of 3 mg/L (Ferrari et al. 2015). Interestingly, Melville (1995) reported a clear shift (the loss of *Bosmina*) in the cladoceran community and pronounced dominance of *Ceriodaphnia reticulata* in a small boreal lake in Canada, which was affected by uranium mine effluent resulting in elevated concentrations of uranium (0.54 mg/L) and sulfate (1140 mg/L) in lake water. These pronounced differences in dominant species in high U and high sulfate lakes suggest that the reasons behind the cladoceran changes are complicated and in addition to water chemistry are probably also related to regional (e.g., climatic) variables.

Cladocera and fuel minerals mining

Black coal, lignite and oil sands

Canton and Ward (1981) reported extremely poor cladoceran community (sole species was *B. longirostris* < 1 individual/L) in a coal mine pond (Pond 1) in NW Colorado USA, which had received mine water (pH 7.4, total dissolved solids (TDS) 3811 mg/L, nitrate 16.34 mg/L) for a decade. In the older pond (Pond 2), with lower contamination levels (pH 7.4, TDS 1770 mg/L, nitrate 0.55 mg/L), the cladoceran community covered more species (*C. sphaericus, D. pulex, B. longirostris*). The cladoceran community of the control site (Pond 4) (pH 7.6, TDS 547 mg/L, nitrate 0.14 mg/L) was devoid of *B. longirostris* and the dominating species was *C. reticulata*, followed by *D. pulex, C. sphaericus and A. guttata.* Whereas the extremely low cladoceran abundance in the most polluted pond (Pond 1) may result either from nitrate or solids pollution, the nitrate levels in other two ponds (Ponds 2 and 4) are well below safe levels (Camargo et al. 2005) suggesting impact due to solids pollution. Because many lignite deposits in central Europe are located in sulfide-rich areas, the abandoned mines once filled with water are prone to acidification and metal pollution (Miller et al. 1996). In Lusatia (eastern Germany) on its own, the number of acidic pit lakes exceeds 400 (Nixdorf et al. 1998). In central Germany lignite mining district, approximately 50% were earlier or currently are acidic (Schultze et al. 2010). Mining pit lakes are occasionally affected by varying dilution regimes or pollution gradients. For example, a strong pH gradient in mining pit lake Lake Senftenberger See (Germany) is reflected in cladoceran species richness along this gradient (Belyaeva and Deneke 2007) with *C. sphaericus* being the only species present along the whole pH range (pH 3–7). The pH tolerance of *C. sphaericus* was also demonstrated by Klapper and Schultze (1995) as they noticed *C. sphaericus* in lignite pit lakes in Germany at the pH of 2.9, whereas *Daphnia* was detected only in lakes with the pH of 6 or higher. In addition, Wollmann et al. (2000)reported *C. sphaericus* from acidic pit lakes Felix (pH 3.6) and L117 (pH 2.8) in Germany. Similarly, Sienkiewicz and Gasiorowski (2016) found that *C. sphaericus* was the only species present in a highly acidic mining lake (Lake TR-33, Poland) before neutralization and subsequent normalization of the cladoceran community. Moser and Weisse (2011) compared zooplankton communities between two meromictic mining lakes in Austria, one of which was neutralized 25 years ago whereas the other had remained acidic (pH 2.6). The acidic lake was devoid of cladocerans, whereas *Daphnia* and *Bosmina* were recorded occasionally in the neutralized lake during the 2-year period. However, the characteristics of the neutralized lake varied inter-annually, resulting in fluctuation between pH 4.3 and 8.0 probably hampering the successful establishment of a rich cladoceran community. The mining pollution impacts on cladocerans, even when pollutants are highly toxic, are not always so straightforward. Kurek et al. (2012) studied cladoceran community changes in six lakes in Alberta, Canada, that have been affected for decades by PAHs (polycyclic aromatic hydrocarbons) input originating from the oil sands mining. However, the major shifts in cladoceran communities occurred before the oil sands mining started and, thus, the effect of PAHs contamination is uncertain.

Cladocera and other mines

Apatite

Vandysh (2004) concluded that the pollution induced by apatite-nepheline tailings and mine water since the 1930s induced a clear shift in cladoceran community in Belaya River watershed located on the Kola peninsula, NW Russia. The author suggested that the tailings-derived turbidity and also the eutrophication resulted in the disappearance of *D. cristata*, *Holopedium gibberum*, *Leptodora kindti* and *Bythotrephes cedestromii*. The most common species in polluted areas was *Bosmina obtusirostris* (syn. *Bosmina (Eubosmina) coregoni*). The loss of large sized species is particularly interesting as the large bodied species are valuable food items for fish but also more vulnerable to fish predation than small bodied taxa (Brooks and Dodson 1965), adding another component to the ecological changes in Belaya River watershed.

Basalt

El-Bassat and Taylor (2007) noted cladoceran species being extremely rare (*B. longirostris*, *Pleuroxus* sp. and *Alona* sp. were detected) in alkaline (pH 7.8–8.5), saline (EC 28,000 µS/cm) and eutrophic Abp Zaabal Lake, which occupies a former basalt mine, in Cairo, Egypt. It must be noted, however, that Abp Zaabal Lake is highly impacted by waste water input unrelated to mining, which prevents any generalizations regarding the role of initial pit lake chemistry on cladoceran community.

Diamonds

The effluent (showing elevated concentrations of Ca^{2+}, K^{+}, $SO_4{}^{2-}$, Na^{+}, Mg^{2+}, $HCO_3{}^{-}$) originating from the Ekati mine, a diamond mine located in northern Canada, was reported to inflict distinct changes in cladoceran communities in the chain of lakes along the pollution gradient. The species, which usually dominates softwater low-Ca lakes in the region, *Holopedium glacialis*, was substituted by *Daphnia longiremis* and *Daphnia middendorfiana* due to elevated pH and Ca enrichment (Griffiths et al. 2018).

Gypsum

Alkaline (pH 7.6–0.7.9) gypsum mine pit lakes in Croatia, with very high concentrations of solids (TDS > 2000 mg/L), calcium ($\sim$ 1300–1400 mg/L) and sulfate ($\sim$ 400–1300 mg/L) were dominated by *Chydorus* sp. and *C. reticulata,* whereas a non-gypsum karst lake (pH 7.9, EC < 482 µS/cm, calcium 240 mg/L, sulfate 12.8 mg/L) was dominated by *B. longirostris* and *Ceriodaphnia quadrangula.* The community difference was suggested to originate from the reduced feeding efficiency in gypsum lakes (Stankovic et al. 2011).

Hematite

Coard et al. (1983) detected the total, but relatively temporal loss of planktonic taxa and subsequent dominance of a chydorid species in a lake located in Cornwall, England, which was affected by hematite–clay input due to mining activities in the early twentieth century. The loss of planktonic taxa may be related to increased concentrations of solids and subsequently decreased feeding efficiency for planktonic filter feeder species (e.g., Arruda et al. 1983; Stankovic et al. 2011).

Sand

Sand and gravel extraction pit lakes in, e.g., Hungary (Vad et al. 2012) and Croatia (Stankovic and Ternjej 2009) harbor relatively rich and diverse cladoceran communities. In addition, one species (*Macrothrix laticornis*), seldom detected in Belgium in the early twentieth century, has been discovered to exploit newly dug sand pits and has thus been able to become relatively widespread (Dumont 1989).

Sulfur

A pit lake, formed due to the abandonment of a sulfur mine in Tarnobrzeg (Poland) is characterized by slightly alkaline pH (7.2–8.6), elevated hardness (1000–2000 mg $CaCO^3$), and the lake is meromictic. *Chaoborus flavicans,* which is an efficient predator and may affect the cladoceran community (Jäger et al. 2011), was detected. The general cladoceran abundance was low and planktonic species *D. cucullata* and *B. longirostris* dominate the cladoceran community (Wilk-Woźniak and Zurek 2006). This particularly interesting case would deserve long-term monitoring study or paleolimnological study to examine the roles of meromixis, water chemistry and predation on cladoceran community structure.

Cladocera in mine water research

The available literature regarding the impacts of mine water on cladoceran communities in lake environments is still rather scarce. Moreover, only 11 of the reviewed studies included an adequate temporal dimension to allow the analysis of the community dynamics, which constitutes vital information regarding impact assessments or restoration planning. There seems to be few regional hotspots where cladoceran communities and mining pollution have been studied in natural waters (Table 1). This regional variation in cladoceran studies is probably related to the number of lakes in different regions. Most important stressors in reviewed papers were acidity, metals and salinity or solids. In most cases, species shifts or changes in productivity are reported. In addition to direct toxic impacts inflicted by high aquatic concentrations of harmful elements, also low concentrations of harmful elements (or changes in lake chemistry regarding non-toxic constituents) or other ecological changes may result in distinct impacts in cladoceran populations. The stress induced by exposure to elevated salinity has been reported to interfere with cladoceran reproduction (Elphick et al. 2011; Van Dam et al. 2014), whereas cladoceran growth is negatively affected by changes in food availability (mineral ingestion instead of edible particles; Maia-Barbosa and Bozelli 2005) and in food quality (e.g., increased abundance of cyanobacteria; Lundstedt and Brett 1991). Declining clutch sizes and inhibited growth are reflected in cladoceran productivity. The most sensitive taxa disappear first, which is reflected in diversity. Because cladocerans rely on sedimentary egg banks as temporal refugia to bypass seasonal or ecological “hardships” (e.g., winter or crowding), the sedimentary pollution may also have a pronounced impact on cladoceran communities (Rogalski 2015).

The most tolerant species regarding mine water impact belong to the *Chydorus* and *Bosmina*—groups. Namely, *C. sphaericus* is clearly able to thrive in acidic lakes, whereas *Bosmina* sp. does not exhibit special tolerance to any particular pollutant but seems to tolerate solids pollution relatively well. Comprehensive autecological analysis has not been published for either *B. longirostris* or *C. sphaericus* but according to (Błędzki and Rybak 2016) *Chydorus* cf. *spahericus* and *Bosmina* spp. are wide spread and abundant in many types of water bodies both in littoral and pelagial zone with high stress tolerance.

The applicability of cladocera as bioindicators/biomonitors

As defined by Markert et al. (2003), bioindicators are organisms (or, e.g., communities) that contain information on the quality of the environment, whereas biomonitors are organisms (or, e.g., communities) that contain information on the quantitative prospects of the environment. Thus, biomonitors are always bioindicators as well. In general, cladocerans fulfill many of the characteristics that are deemed important for any bioindicator organism. Namely, cladocerans are sensitive to pollution (Von Der Ohe and Liess 2004) and have short life cycles (Smirnov 2017), resulting in rapid responses to environmental stress. Recently, cladocerans have been used to study community level responses to environmental variables in many types of environments, e.g., dystrophic lakes in central Europe (Zawisza et al. 2016), subarctic lakes in Finland (Leppänen et al. 2016) and crater lakes in western Uganda (Rumes et al. 2011). The potential of cladocerans as a community level indicator tool in mining pollution studies is highlighted in the results of this review as the community shifts are clearly visible in most of the studies which span from pre- to post impact conditions. In addition, most of the results indicate distinct differences between impacted and reference sites. However, whether the overall conditions of an ecosystem can be determined by studying only one group of organisms is

Table 1 General characteristics of mine pollution and impacts on cladoceans

Country	Mine	Pollution type	Study type	Pollution characteristics	Dominant species during impact	Other notes	Citation
Austria	Lignite	Pit lake	Descriptive	Impacted lake low pH, reference lake neutralized. Both meromictic, and internannual pH variation	No cladocerans	*Daphnia* and *Bosmina* only occasionally detected in reference lake	Moser and Weisse (2011)
Brazil	Uranium	Effluent	Comparison	High U, low pH, high conducitivty in impacted site	*Bosmina* sp.	*Bosmina* and *Diaphanosoma* detected in reference site	Ferrari et al. (2009)
Brazil	Uranium	Effluent	Descriptive	High U, low pH, high conducitivty, high sulfate in impacted site	*Bosmina* sp. and *Bosminopsis deitersi*	Low density	Ferrari et al. (2015)
Brazil	Bauxite	Tailings	Comparison	Fine particulate tailings of Al and Fe oxides	*Diaphanosoma polyspina, B. deitersi, Bosmina hagmanni, Ceriodaphnia cornuta, Moina minuta*	Density and brood size oscillate more in the impacted area	Bozelli (1996)
Brazil	Bauxite	Tailings	Comparison	Fine particulate tailings of Al and Fe oxides	*Diaphanosoma birgei, B. deitersi, B. hagmanni, C. cornuta, M.minuta*	Size and weight affected by tailings in impacted area	Maia-Barbosa and Bozelli (2005)
Brazil	Kaolinite and Iron	Effluent	Descriptive	Effluents with near neutral pH, varying elemental concentrations originating from two mines	*Bosmina longirostris* and *Eubosmina tubicen*	More diverse community in Iron mine reservoir	Moreira et al. (2016)
Canada	Copper	Effluent	Continuous	Low pH and elevated metals concentration	*B.longirostris*	Community reduction due to pollution	Doig et al. (2015)
Canada	Iron	Effluent	Continuous	Elevated metals concentrations	*B.longirostris, E. longispina*	Decreased cladoceran species richness	Winegardner et al. (2017)
Canada	Uranium	Effluent	Continuous	High U, elevated salinity and metals concentration	*Ceriodaphnia reticulata*	Loss of cladoceran diversity	Melville (1995)
Canada	Oil sands	Effluent	Continuous	PAHs contamination	*Daphnia*	Uncertain effects	Kurek et al. (2012)
Canada	Diamonds	Effluent	Comparison	elevatod Ca, K, Mg, Na, SO concentrations in effluent	*Daphnia middendorfiana* and *Daphnia longiremis*	*Holopedium glacialis* dominates the unimpacted lakes	Griffiths et al. (2018)
China	Tin	Effluent	Continuous	Arsenic contamination	*Bosmina* spp.	Cladoceran production decline	Chen et al. (2016)
Egypt	Basalt	Pit lake	Descriptive	Saline, eutrophic pit lake	*B. longirostris*	Very low cladoceran diversity and species richness	El-Bassat and Taylor (2007)
Finland	Gold	Effluent	Comparison	Low pH and elevated metals concentrations	*B. longirostris*	Masked by eutrophication	Leppänen et al. (2017a)

Table 1 continued

Country	Mine	Pollution type	Study type	Pollution characteristics	Dominant species during impact	Other notes	Citation
Finland	Gold	Tailings	Continuous	Mineral tailings	*B. longirostris*	Decline in cladoceran diversity and species richness	Leppänen et al. (2017b)
Finland	Nickel	Effluent	Continuous	Meromictic, elevated salinity and metals concentrations	*B. longirostris*	Low cladoceran diversity	Leppänen et al. (2017c)
Germany	Lignite	Pit lake	Comparison	Low pH	*C. sphaericus*	Species shift along pH gradient	Belyaeva and Deneke (2007)
Germany	Lignite	Pit lake	Descriptive	Low pH	*C. spahericus*		Wollmann et al. (2000)
Germany	Lignite	Pit lake	Comparison	Low pH	*C. spahericus*	Daphnia only in pH 6 and above lakes	Klapper and Schultze (1995)
Poland	Zinc	Effluent	Comparison	Elevated metals concentrations	*Bosmina coregoni*	Extremely poor cladoceran community	Wilk-Wozniak et al. (2011)
Poland	Sulfur	Pit lake	Descriptive	High hardness, meromixis	*Daphnia cucullata* and *B. longirostris*		Wilk-Wozniak and Zurek (2006)
Poland	Lignite	Pit lake	Continuous	Low pH	*C.spahericus*	Cladoceran production and diversity increased due to neutralization	Sienkiewicz and Gasiorowski (2016)
Russia	Iron	Effluent	Comparison	Alkaline effluent, elevated EC and Na, K, Li, Ca, Mg concentrations	*Bosmina sp.*	*Daphnia* dominated reference lake	Holopainen et al. (2008)
Russia	Apatite	Effluent	Comparison	Apatite-nepheline effluent and tailings	*B. coregoni*	Sensitive species disappeared	Vandysh (2004)
UK	Granite	Tailings	Continuous	Hematite-clay	*Chydorids*		Coard et al. (1983)
USA	Copper	Effluent	Continuous	Copper pollution		Decline in *Bosmina* production	Kerfoot et al. (1999)
USA	Iron	Tailings	Continuous	Hematite and limonite particles	*C. sphaericus*		Bradbury and Megarad (1972)

Table 1 continued

Country	Mine	Pollution type	Study type	Pollution characteristics	Dominant species during impact	Other notes	Citation
USA	Coal	Tailings	Comparison	High concentration of solids, high N	*B. longirostris*	Very low diversity and richness	Canton and Ward (1981)

Study type denotes whether a study is descriptive without comparison to non-impacted reference, comparative (e.g., non-impacted lake versus impacted lake) or continuous with adequate temporal dimension to allow the assessment of community changes the central question in every bioindicator application (Markert et al. 2003) but due to the central location in food webs, the cladoceran community has the potential to reflect the surrounding environment in great detail.

The suggested endpoints for community level bioindicator studies are food web structure shifts or changes in species diversity (Harwell et al. 1987). With cladocera, the food web structure shifts (e.g., change in predator regime) are reflected in size structure in cladoceran community (Brooks and Dodson 1965) and to morphological changes among some species (Korosi et al. 2013). The increased dominance of the most tolerant taxa is reflected in diversity and richness indices due to the disappearance of rare or sensitive species from the community. Distinct changes in species composition (e.g., total loss of macrophyte associated species) may indicate the destruction of habitat (e.g., pronounced decline in macrophyte cover). However, it is challenging to determine whether a community has factually changed due to mine water input and what criteria should be used to detect the change. Namely, the natural variability of pre-disturbance community, disturbance impact and the post-disturbance community dynamics must be assessed. This can be achieved either by long term monitoring (e.g., Stow et al. 1998; Lindenmayer and Likens 2009), which are very rare, or paleolimnology (e.g., Smol 1992; Saros 2009). Luckily, historical cladoceran community can be reconstructed using paleolimnological methods (Korhola and Rautio 2001) and, in fact, the group is deemed a powerful tool for environmental reconstruction (Tolotti et al. 2016). Another highly important information, i.e., the exact point (or time) of community change, can be determined by applying statistical methods, such as broken-stick zonation (Bennett 1996), where significant changes in community are pinpointed or analysis of similarities, ANOSIM (Clarke 1993), which can be used as a test of significant difference between pre- and post-pollution communities. The perpetuity of the shift can be assessed by post-disturbance research (e.g., if the community recovers to its pre-disturbance form or is shifted to a new steady state). The information regarding pre-disturbance community (e.g., Battarbee 1999) and the possible recovery dynamics are of vital importance also in restoration and management purposes (European Union 2000). It must be noted that after the disturbance, the new community structure depends on source populations for recolonization and, thus, the niche availability (e.g., whether the most important niches are re-occupied or not) should be taken into account in addition to actual post-disturbance species composition.

Unfortunately, the reviewed literature does not allow the reliable identification of most vulnerable species, which could be used as early warning tools in mining pollution research. Partly, this is a result of incomplete reporting of cladoceran community. In many studies, only the dominant species were recorded and potentially very interesting data regarding most sensitive species were not available. In addition to community level considerations, widely distributed and highly resistant taxa *C. sphaericus* and *Bosmina* spp. may be successfully used as individual indicators. However, to further explore the potential of these two taxa as mine water indicators, more research (e.g., morphological changes due to pollution, population impacts, and life history changes) with *Bosmina* and *Chydorus* is needed. Luckily, some of this work has already been started (e.g., sedimentary toxicity test for *C. spahericus* has been developed; Dekker et al. 2005) but both of those groups are deemed challenging in terms of taxonomy (Belyaeva and Taylor 2009; Adamczuk 2016) which will hamper the applicability of *Bosmina* and *Chydorus* as global or regional indicators until the taxonomic issues are clarified. Moreover, as pointed out by Markert et al. (2003) bioindicator community or species level responses should be compared and "calibrated" to determine the indicator applicability of same species or species groups across regions and ecosystems. In addition to toxicological aspect, cladocerans can also be used in biomagnification studies (Stewart et al. 2008) and food web impact research (Draves and Fox 1998) in mine water studies. An interesting species, worth mentioning, is halophylic *Daphnia exilis*, which has been detected in reservoirs impacted by copper mine pollution in Chile (Heine-Fuster et al. 2010) and could thus be used as an indicator of saline mine drainage in the natural distribution area of this species.

Further reading

Besides the literature reviewed here, there are additional important resources for anyone working with cladocerans and mine pollution: The current role of cladocerans in ecotoxicological research in general has recently been reviewed by Sarma and Nandini (2006) and Suhett et al. (2015). In addition, the most important cladoceran species in toxicology research is *Daphnia*, which was extensively reviewed by Lampert (2011). Adamczuk (2016) reviewed *Bosmina longirostris*, one of the most important species when pollution impacts on cladoceran species composition are studied. Moreover, extensive data on mortality and reproduction in response to increasing concentrations of toxicants are available from databases, such as ECOTOX (2017). Detailed contribution on cladoceran physiology, where deeper look into the impact of xenobiotics is provided, was presented by Smirnov (2017). In addition to mine water impact, mining industry has also other effects on cladoceran communities. The lakes in the Sudbury mining region have been rigorously studied and the impacts of pollution originating from smelting and roasting processes on cladocerans have been assessed in many papers (e.g., Labaj et al. 2014, 2015; Thienpont et al. 2016). These studies would be a great benefit for anyone interested in cladocerans and mining pollution.

Conclusion

Clearly, there is a need to conduct further research in the field. The most interesting and necessary aspect is related to most sensitive species. Thus, it would be highly preferable if researchers published full species composition data even in cases, where only selected taxa are being studied in greater detail. Cladoceran potential as community level indicators is another issue which deserves more attention in research. For example, cladoceran community studies utilizing spatial and temporal aspects along pollution gradient could hold great potential in this sense. Finally, ecotoxicological research regarding the most tolerant taxa (*Chydorus sphaericus* and *Bosmina longirostris*) in natural setting is of utmost importance, but this should be preceded by clarification of the taxonomical issues of those species.

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